The Electron–Phonon Scattering Rate in Thin Free-Standing Metallic Films

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There exists much controversy in the literature regarding the origin of various power laws manifested in the electron-phonon scattering rate (τ_{ep}^{-1}) in metallic films. From theory for bulk systems [1], τ_{ep}^{-1} varies as T^3 or T^4 for the clean or dirty limit, with the power decreasing by T^1 for systems with a 2D phonon excitation spectrum. Experimentally observed power laws for τ_{ep}^{-1} range from 1.4 to 3.7. Typically, the lower values have been attributed to phonons whose excitation spectrum is significantly altered. However, there have been few attempts to systematically explore this hypothesis by varying the sizes.

In this paper, we compare τ_{ep}^{-1} from two experiments. In one, we measure the thermal resistance introduced by the electron-phonon scattering process in thin copper films [2]. In the second, we examine the magnetoresistance of thin aluminum films to determine the inelastic scattering rate which is dominated by τ_{ep}^{-1} [3]. We always compare the rates in free standing and supported films, fabricated simultaneously and with nearly identical physical properties. We expect that the phonon density of states should be 2D for free standing films of thickness d when the thermal phonon wavelength, $\lambda > 2d$. We can express this condition by the relation, $T < hc_s/2d\, k_B$ (c_s is the sound velocity).

The films were deposited on a nitrided wafer, and by a combination of wet and reactive ion etching, the substrate under part of the film was removed, leaving a free standing segment contiguous with an identical supported segment [4].

Electron-heating measurements carried out on copper films show a thermal resistance which varies as T^{-3} for both supported and free-standing films, when the latter are immersed in helium or coated with a few monolayers of helium. The expected bulk dependence for the supported films is T^{-4}. Through a number of checks detailed elsewhere [2], we established that the thermal resistance can be attributed to the electron-phonon scattering rate and not to boundary resistances. The results of these measurements are shown in figure 1a. We also examined thinner and narrower films as well as thicker films which should have exhibited reduced dimensional behavior at different temperatures. In all cases we find that $\tau_{ep}^{-1} = 3 \times 10^8\, T^2\, s^{-1}\, K^{-2}$, was independent of the film thickness and width.

It was known that the inelastic scattering rate of thin aluminum films shows a T^{-3} power law on substrates, consistent with the coupling of the substrate phonons into the thin film [5]. In figure 1b, we plot the results of our experiments illustrating that the inelastic scattering rate ($\tau_{in}^{-1} \approx \tau_{ep}^{-1} = 1.4 \times 10^7\, T^3\, s^{-1}\, K^{-3}$) is unaffected by whether the films are free standing or supported. We also include the results of a calculation to estimate the temperature dependence of τ_{ep}^{-1} in the

Springer Series in Solid-State Sciences, Volume 112
Phonon Scattering in Condensed Matter VII Eds.: M. Meissner and R.O. Pohl

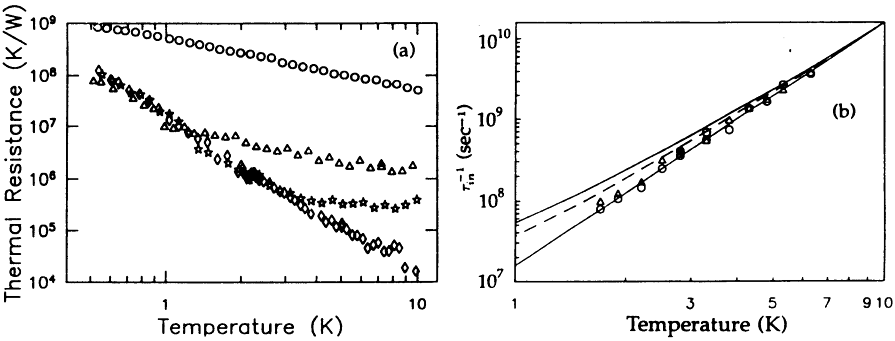

Fig. 1. (a) The thermal resistance for energy transport out of the electron gas in 20nm thick copper films. (◇) Supported film, (○) free standing films in vacuum, (△) Free standing film covered with 3 to 4 monolayers of ^{4}He, (⋆) free standing films immersed in liquid helium. In (b) we show the inelastic scattering rates for supported (△) and free standing (○) aluminum films. The upper solid line is the expected result for free standing films accounting for only longitudinal phonons. The dashed line includes transverse as well as longitudinal phonons. Both sets of results in (a) and (b) show no significant crossover effects due to dimensionality constraints.

aluminum films [3], which shows that below 3 K there should be a significant difference between the τ_{ep}^{-1} in free standing and supported films.

From the experiments described in this paper, we draw two conclusions. First, there is no simple explanation for the disparity in the power laws for τ_{ep}^{-1} exhibited by the thin copper and aluminum films. Second, we find that the power law of the electron-phonon scattering rate is unaffected by the constraints imposed by finite size. The observation of the insensitivity to the phonon dimensionality using two different experiments supports the conclusion that the understanding of the electron-phonon interaction in thin films is incomplete.

This research was supported by the NSF through DMR-90-16301 and the Cornell MSC under DMR-88-18588.

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